

Search for Leptoquarks

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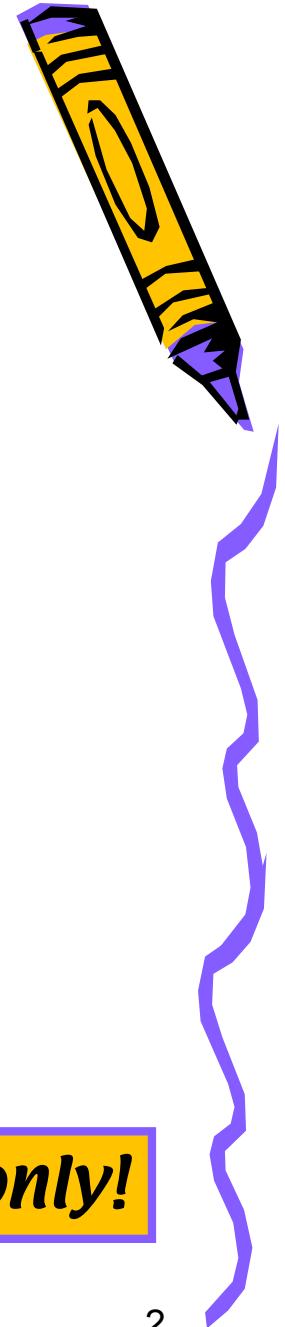
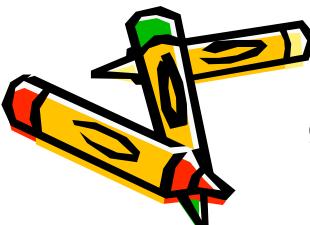
Tev4LHC, Fermilab September 16, 2004



Outline

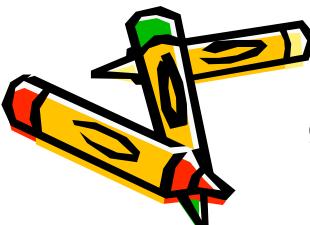
- Why Leptoquarks ?
- Current Results from the TeVatron
 - Final Run II results
- Prospects at LHC
 - Effects of pileup
- Conclusions

1st and 2nd generation scalar LQ only!



Theoretical motivation

- Leptoquarks (LQ) are hypothetical particles which appear in many SM extensions to explain symmetry between leptons and quarks
 - SU(5) GUT model
 - superstring-inspired models
 - 'colour' SU(4) Pati-Salam model
 - composite models
 - technicolor
- LQs are coupled to both leptons and quarks and carry SU(3) color, fractional electric charge, baryon (B) and lepton (L) numbers

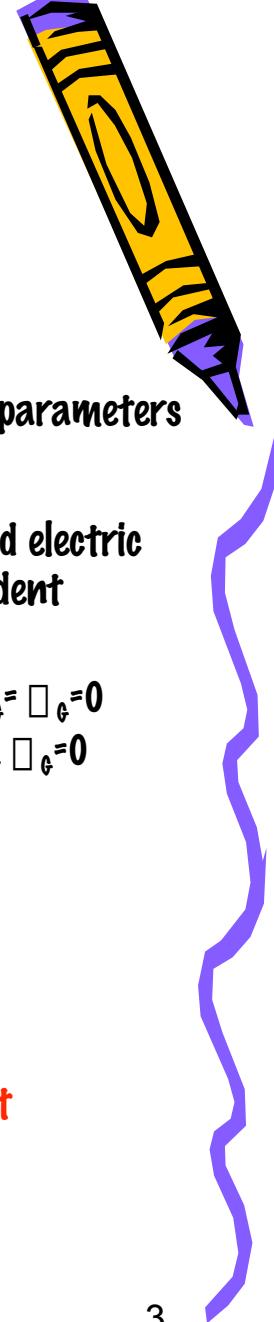


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- LQs can have:
 - spin 0 (scalar)
 - couplings fixed, i.e., no free parameters
 - spin 1 (vector)
 - anomalous magnetic (k_g) and electric quadrupole (\square_g) model-dependent couplings
 - Yang-Mills coupling: $k_g = \square_g = 0$
 - Minimal coupling: $K_g = 1, \square_g = 0$
 - Experimental evidence searched:
 - indirectly: LQ-induced fermion interactions
 - directly: production cross sections at collider experiments

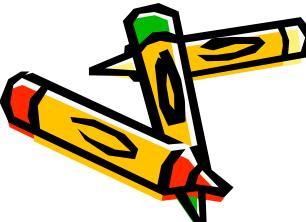
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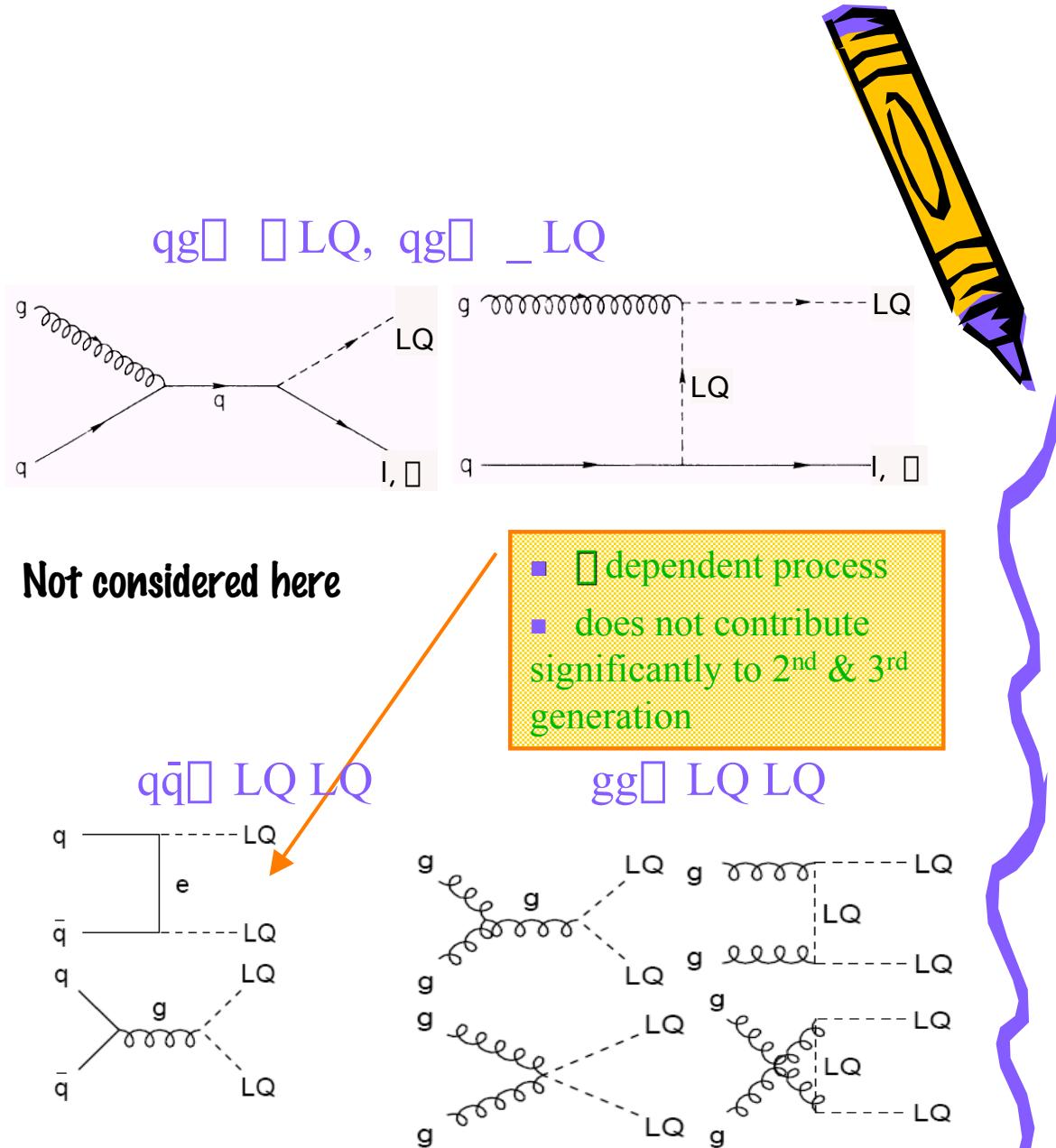


LQ at LHC

- **Single production**
 - strongly depends on λ
 - possible signatures:
 - $l^+ l^- + \text{jet}$
 - $l^+ l^- + \text{jet}$
 - $\nu \bar{\nu} + \text{jet}$
 - Main background: Zjet & $t\bar{t}$
- **Pair production**
 - Practically independent of Yukawa coupling (only g -LQ-LQ vertex)
 - Depends mainly on LQ mass



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Leptoquark Decay

Each generation can decay into 3 final states:

$b = 1$

1st Generation

$$LQ \bar{LQ} \rightarrow e^- e^+ q\bar{q}$$

$b = 0.5$

$$LQ \bar{LQ} \rightarrow e^\pm v_e q_i q_j$$

$b = 0$

$$LQ \bar{LQ} \rightarrow v_e v_e q\bar{q}$$

2nd Generation

$$LQ \bar{LQ} \rightarrow \mu^\pm \mu^\mp q\bar{q}$$

$$LQ \bar{LQ} \rightarrow \mu^\pm v_\mu q_i q_j$$

$$LQ \bar{LQ} \rightarrow v_\mu v_\mu q\bar{q}$$

3rd Generation

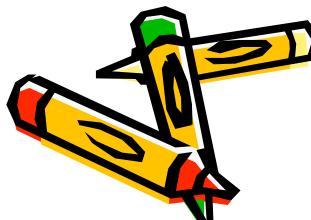
$$LQ \bar{LQ} \rightarrow \tau^\pm \tau^\mp q\bar{q}$$

$$LQ \bar{LQ} \rightarrow \tau^\pm v q_i q_j$$

$$LQ \bar{LQ} \rightarrow v_\tau v_\tau q\bar{q}$$

This talk! →

$$\begin{array}{cccc} LQ & LQ & \square & l l q\bar{q} \\ LQ & LQ & \square & l \square q\bar{q} \end{array}$$



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$$LQ \bar{LQ} \square \square q\bar{q}$$

$$\begin{array}{c} 2l + 2j \\ l + MET + 2j \end{array}$$

$$MET + 2j$$

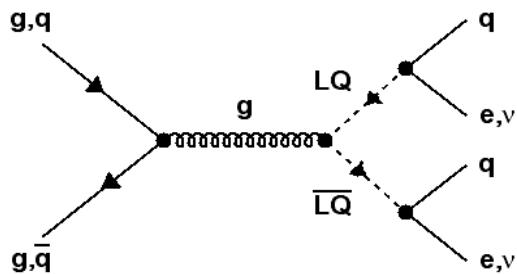
$$\begin{array}{c} BR = \square^2 \\ BR = 2\square(1-\square) \end{array}$$

$$BR = (1 - \square)^2$$

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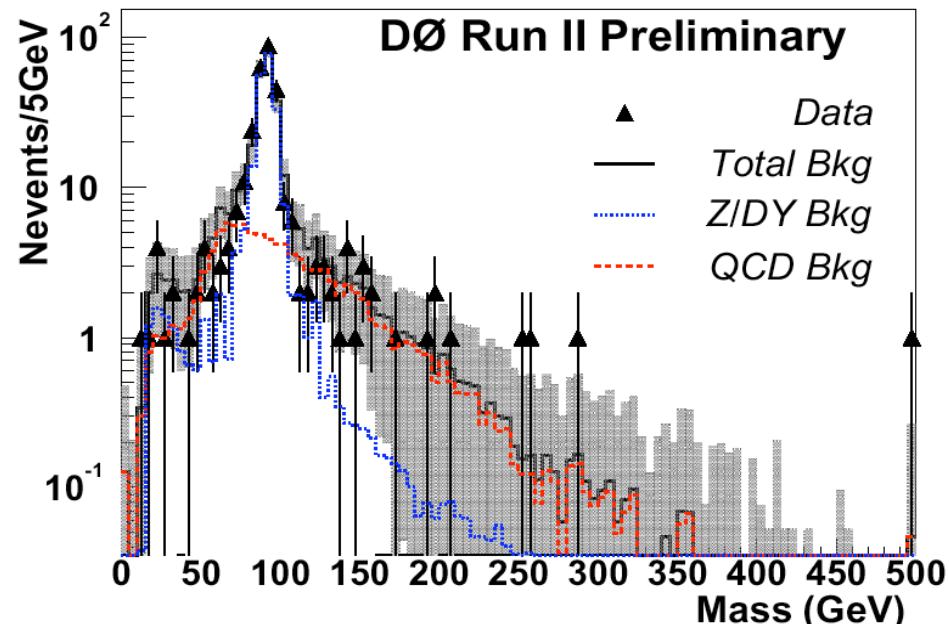


First Gen - eejj at D \emptyset



SM background

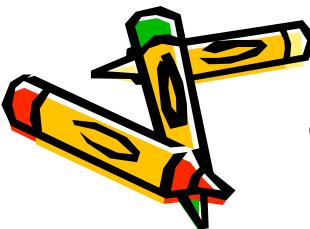
- Drell-Yan+2jets
- Top ($W\rightarrow e\bar{\nu}$)
- QCD/Fakes



Preliminary Selection

- ✓ 2 EM clusters $E_T > 25$ GeV (1 cluster w/ track match)
- ✓ 2 jets $E_T > 20$ GeV
- ✓ Z veto ($80 < M_{ee} < 102$) GeV

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DØ - $eejj$ Results

Final event Selection

Scalar Sum of objects E_T $S_T(eejj) > 450 \text{ GeV}$

Signal Acceptance $\sim (12 - 33)\%$

$M(LQ) \sim 180 - 280 \text{ GeV}/c^2$

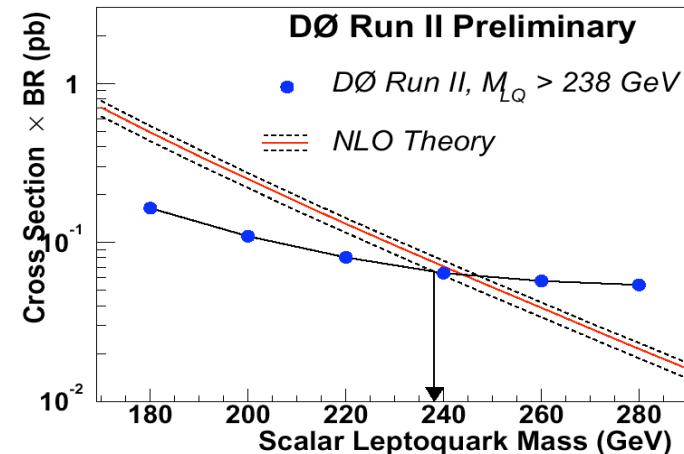
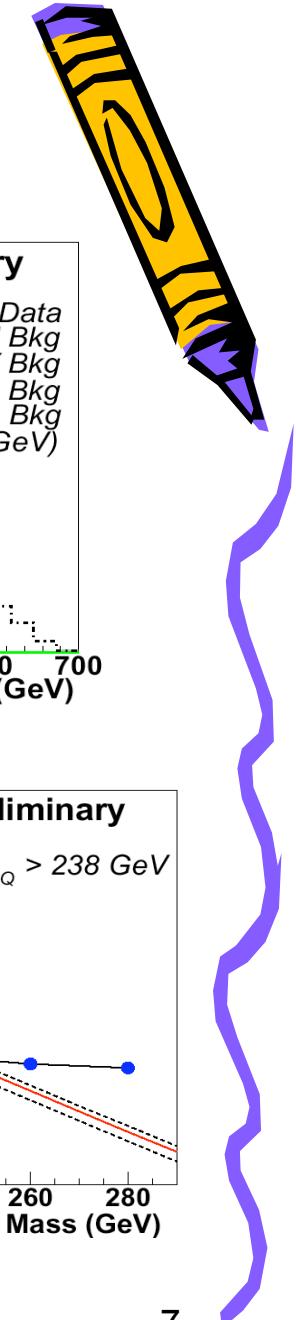
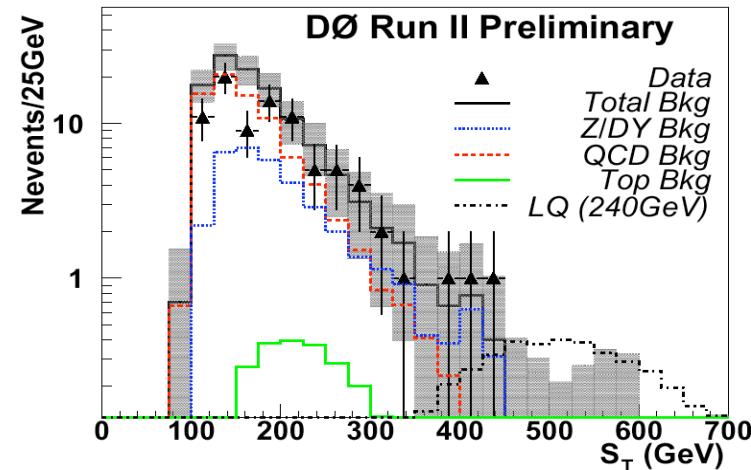
No. Exp.
Observed

0.4 ± 0.1
0

95% CL $M_{LQ} < 238 \text{ GeV}/c^2$



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CDF - eejj

CDF Selection

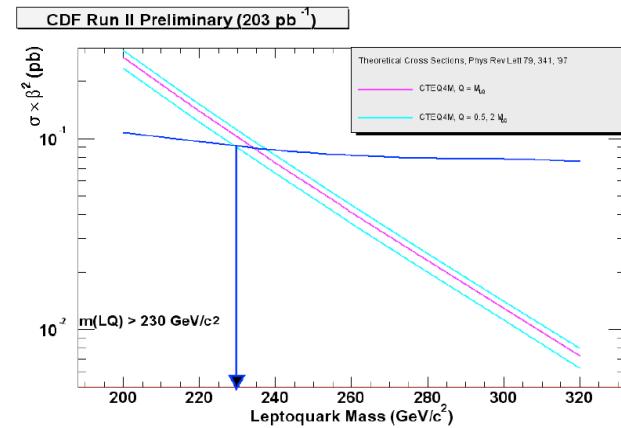
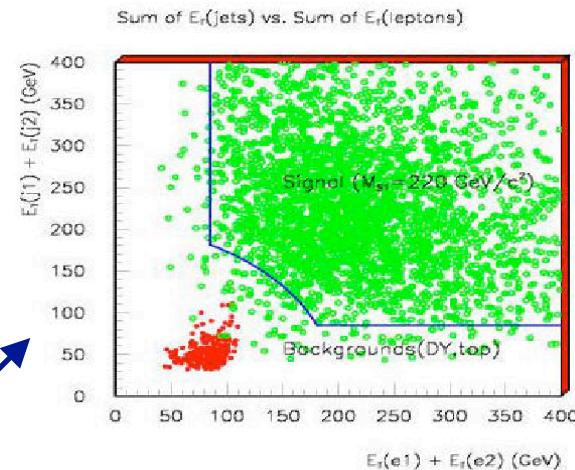
- ✓ 2 electrons (CC,CE) $E_T > 25 \text{ GeV}$
- ✓ 2 jets, $E_T(j1) > 30 \text{ GeV}$, $E_T(j2) > 15 \text{ GeV}$
- ✓ Z Veto ($76 < M_{\mu\mu} < 110 \text{ GeV}$)

- ✓ Muon/Jets: $E_T(j1(e1)) + E_T(j2(e2)) > 85 \text{ GeV}$
- ✓ $((E_T(j_1) + E_T(j_2))^2 + (E_T(e_1) + E_T(e_2))^2)^{1/2} > 200 \text{ GeV}$

Signal Acceptance $\sim (32 - 40)\%$

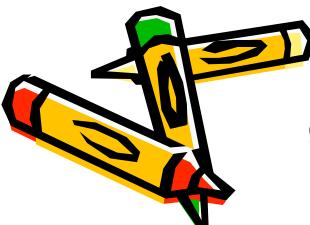
$M(LQ) \sim 200 - 320 \text{ GeV}/c^2$

Luminosity	203 pb^{-1}
Acceptance	$(32-42)\%$
Background	$6.2^{+3.1}_{-2.5}$
Observed	4



Exclude at 95% CL $M_{LQ} < 230 \text{ GeV}/c^2$

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DØ Search - $e j \bar{e} j$

SM background

- W + 2 jets
- Top (l + jets and dilepton)
- QCD/Fakes

Signal Acceptance $\sim (13 - 25)\%$

$m(LQ) \sim 160 - 280 \text{ GeV}/c^2$

Luminosity	175 pb^{-1}
Background	4.7 ± 0.8
Observed	2



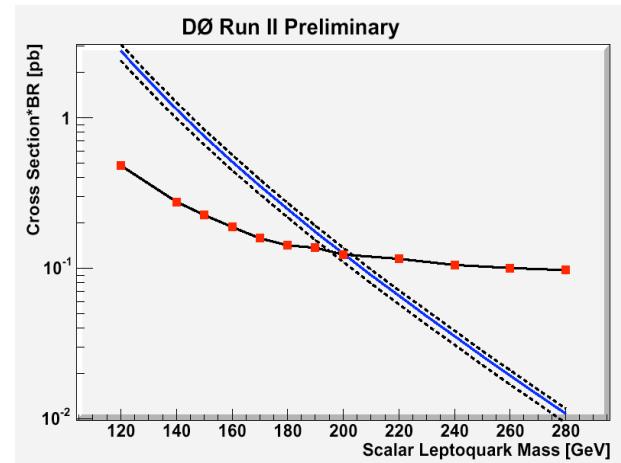
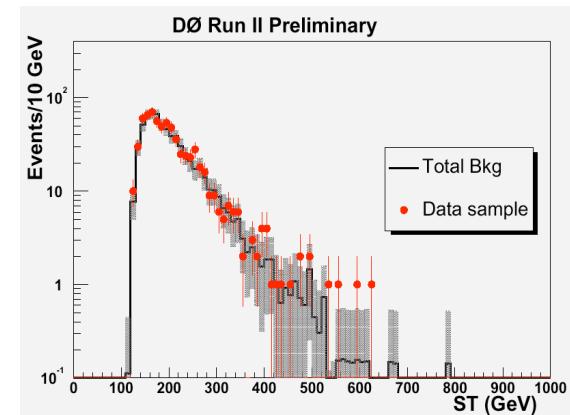
$m_{LQ} < 194 \text{ GeV}/c^2$ @ 95% C.L.

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Selection

- ✓ 1 electron (w/ em cluster - track match) $E_T > 35 \text{ GeV}$
- ✓ MET $> 30 \text{ GeV}$
- ✓ 2 jets $E_T > 25 \text{ GeV}$
- ✓ $D\Phi(\text{MET}, \text{jet}) > 8^\circ$
- ✓ $S_T(j_1, j_2, e, \text{MET}) > 330 \text{ GeV}$
- ✓ $M_T(e, v) > 130 \text{ GeV}$



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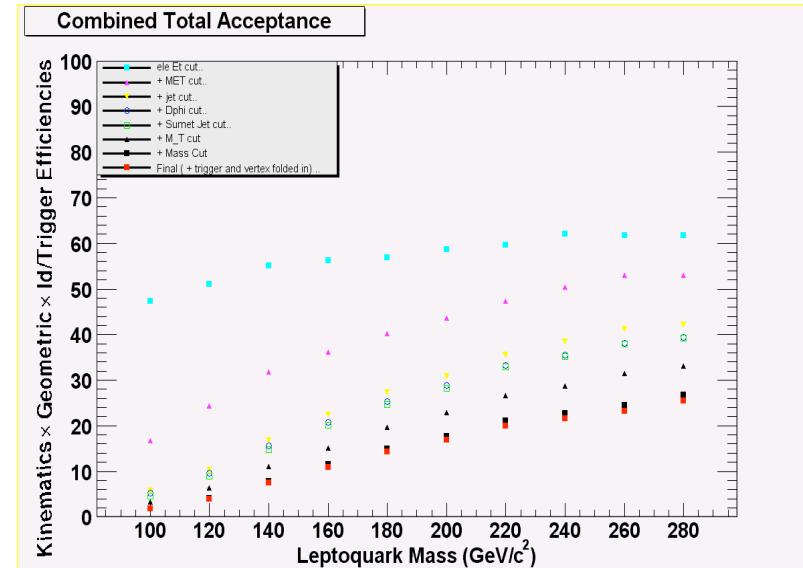
CDF - $e \square jj$

Selection

- apple 1 central electrons with $E_T > 25$ GeV
- apple MET > 60 GeV
- apple Veto on 2nd electron, central loose or Plug
- apple 2 jets with $E_T > 30$ GeV
- apple $\square\square(\text{MET-jet}) > 10^\circ$
- apple $E_T(j1) + E_T(j2) > 80$ GeV
- apple $M_T(e-\square) > 120$
- apple LQ mass combinations

Signal Acceptance ~2 - 22%

$m(LQ) \sim 100-280$ GeV/c²



The invariant mass of the electron-jet system and the transverse mass of the neutrino-jet system are selected where the jet assignment is made such that the difference between the electron-jet mass and the neutrino-jet transverse mass is minimized.



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CDF - $e\bar{q}jj$ - Mass combination

The peak of the $e\bar{q}$ histogram is fitted with a gaussian

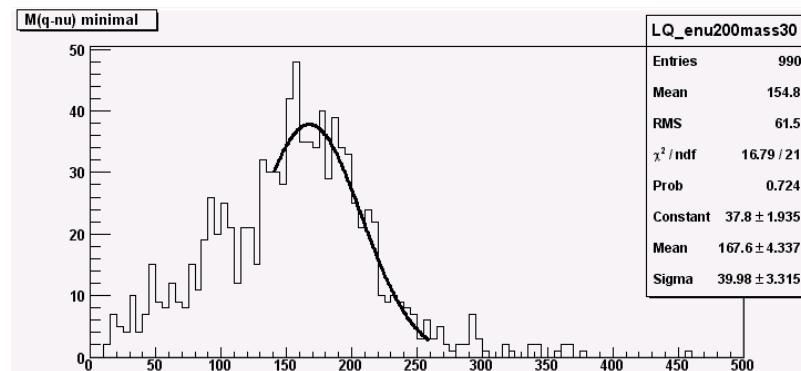
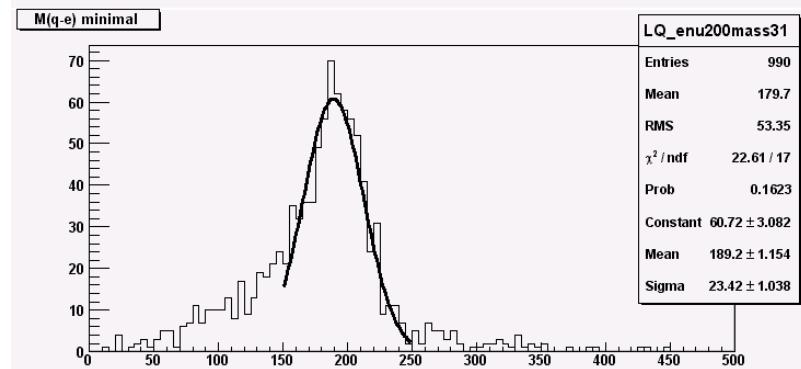
rough estimate of the spread of the distribution in the signal region.

Several masses (120-160-200-240-280) tested:

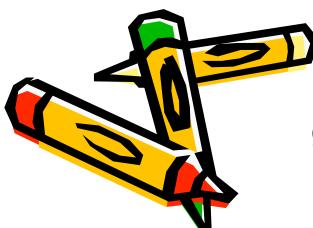
$\Delta_e \sim 15\%$.

The $\bar{q}q$ transverse mass distribution is fitted including the high mass tail end, with a Gaussian to estimate the signal spread.

$\Delta_{\bar{q}} \sim 25\%$.

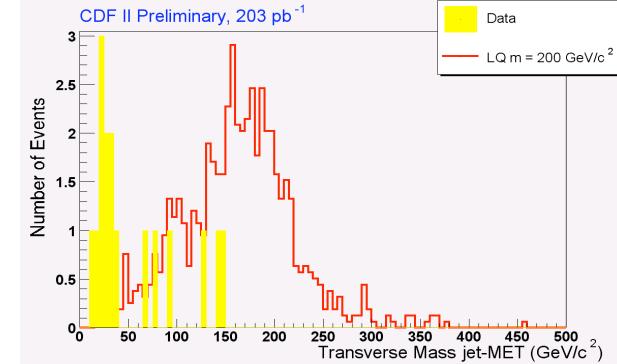
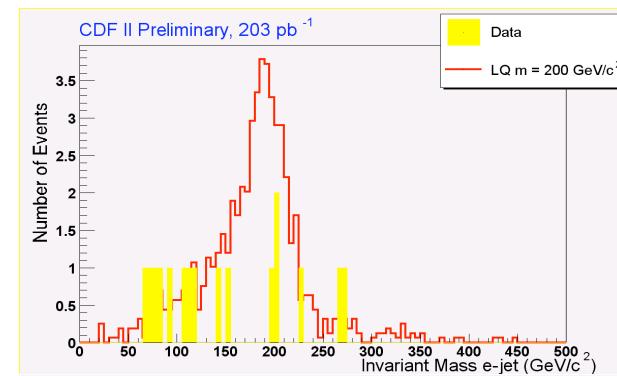
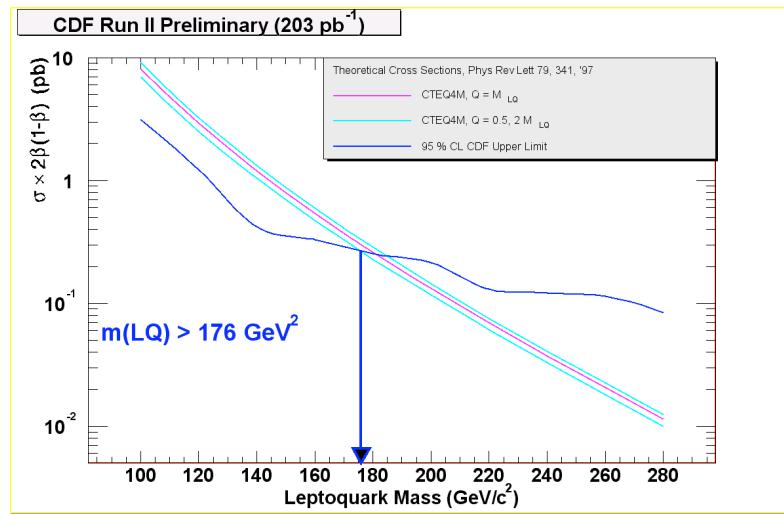


3 σ cut around the nominal mass to select LQ candidates of a given mass



CDF - $e\bar{q}j$ Results

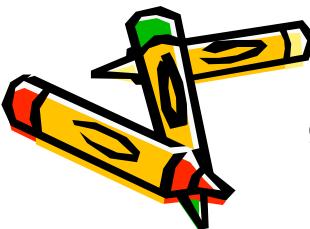
Mass	100	120	140	160	180	200	220	240	260	280
W+2 jets	1.5±0.9	1.5±0.9	1.5±0.9	2.5±1.13	2.5±1.13	2.5±1.13	2.0±1.0	2.0±1.0	1.5±0.88	0.5±0.5
top	2.7±0.6	3.3±0.6	3.12 ±0.5	2.8±0.5	2.5±0.5	2.03 ±0.4	1.63 ±0.4	1.08 ±0.3	0.8 ±0.22	0.6 ±0.21
Z+jets	0.05 ±0.01	0.05±0.01	0.08±0.02	0.08±0.02	0.08±0.02	0.08±0.02	0.06±0.02	0.06±0.02	0.04±0.01	0.04±0.01
Total Data	4.3±1.03	4.9 ±1.05	4.7 ±1.1	5.4 ±1.2	5.0 ±1.2	4.6 ±1.23	3.7 ±1.06	3.1 ±1.0	2.3 ±0.9	1.1 ±0.6
	7	6	4	4	4	4	2	2	2	1



Luminosity 203pb^{-1}

Exclude at 95% CL $M_{LQ} < 176 \text{ GeV}/c^2$

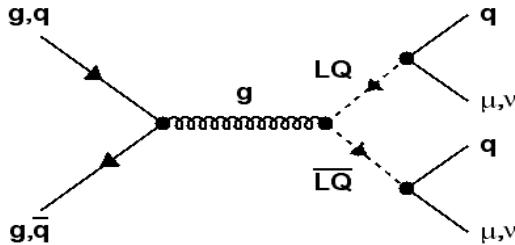
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2nd Gen. -- $\mu j \mu j$ CDF Search

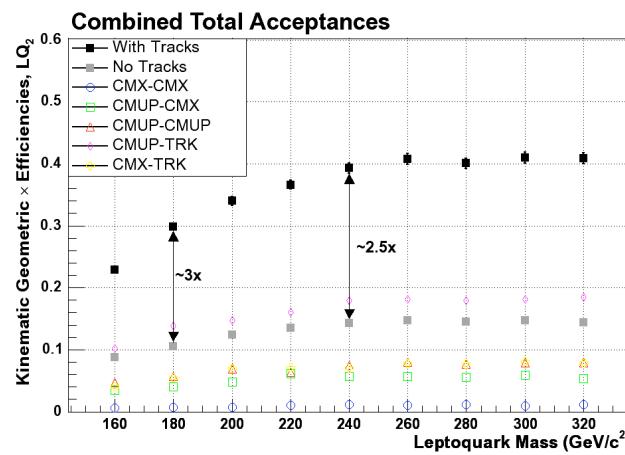
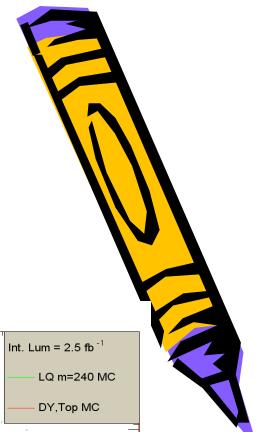
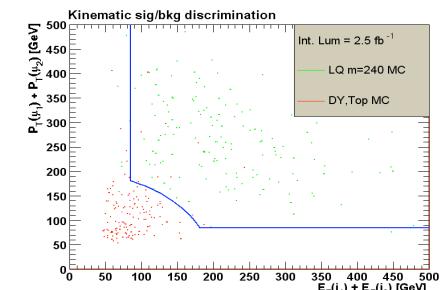


SM Backgrounds

- Drell-Yan+2jets
- Fakes
- Top (W \square $\square\square$)

Selection

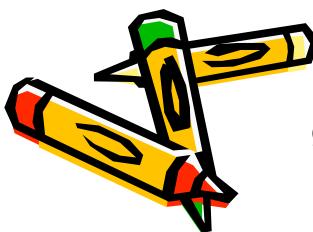
- ❖ 2 muons with $P_T > 25$ GeV
- ❖ 2 jets with $E_T(j_1, j_2) > 30, 15$ GeV
- ❖ Dimuon Mass Veto:
- ❖ $76 < M_{\mu\mu} < 110, M_{\mu\mu} < 15$ GeV
- ❖ $E_T(j_1) + E_T(j_2) > 85$ GeV and $P_T(\mu_1) + P_T(\mu_2) > 85$ GeV
- ❖ $((E_T(j_1) + E_T(j_2))^2 + (P_T(\mu_1) + P_T(\mu_2))^2)^{1/2} > 200$ GeV



Luminosity
Background
Observed

198 pb^{-1}
 3.1 ± 1.2
2

Exclude at 95% CL
 $M_{\text{LQ}} < 241 \text{ GeV}/c^2$

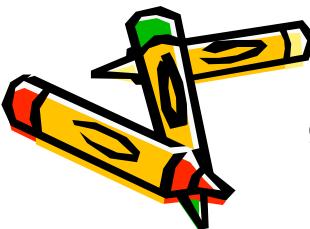
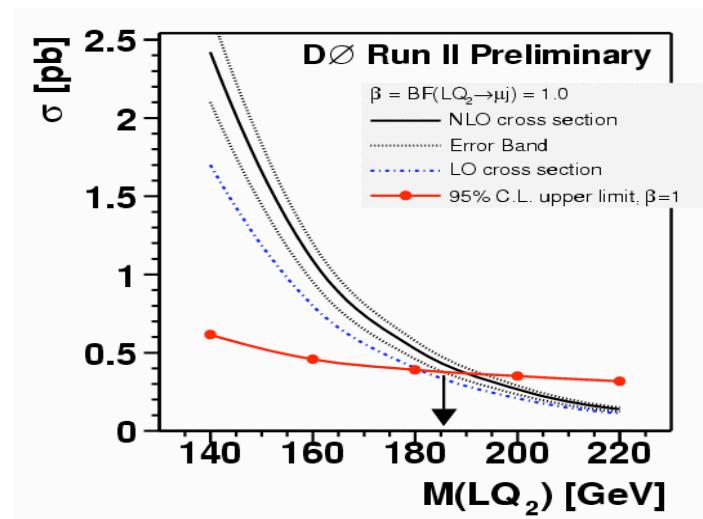
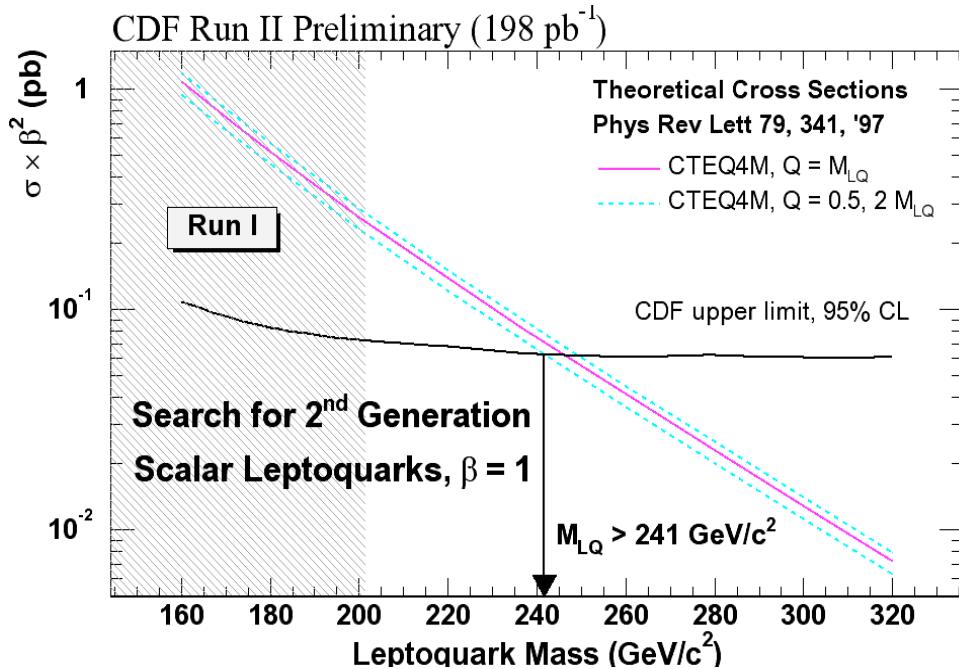


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2nd Gen. -- $\mu j \mu j$ Results



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CDF - $\square\square jj$

SM background

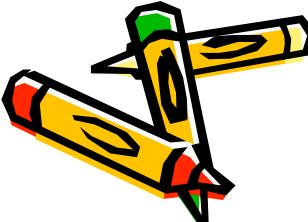
- W +2jets
- Top (l + jets and dilepton)
- QCD/Fakes

$$|M(\mu, j_1) - M_{LQ}| < 2\sigma_1$$

or

$$|M(\mu, j_2) - M_{LQ}| < 2\sigma_2$$

Sigma's determined from generator-level matched reconstructed objects.



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Selection

- Z veto (tight/loose pair)
- No 2nd muon (CMUP, CMX, or stubless)
- $P_T(\mu) > 25 \text{ GeV}$
- $E_T > 60 \text{ GeV}$
- 2 jets, @ $E_T > 30 \text{ GeV}$
- $\Delta\phi(\mu, E_T) < 175^\circ$, $\Delta\phi(E_T, \text{jets}) > 5^\circ$
- $E_T(\text{jet1}) + E_T(\text{jet2}) > 80 \text{ GeV}$
- $M_T(E_T, \text{Muon}) > 120 \text{ GeV}/c^2$

Mass Cut

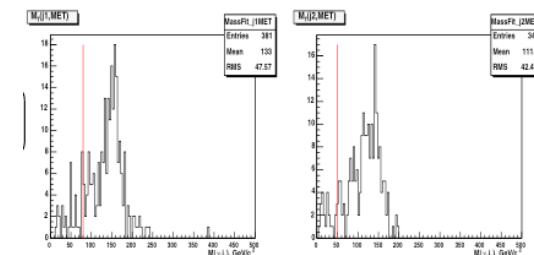
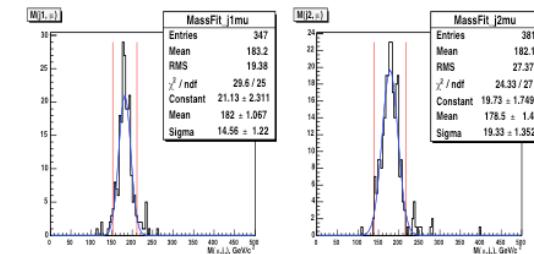
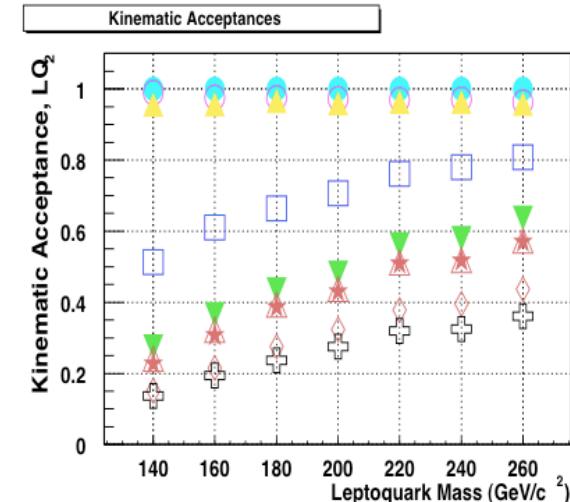
$$M_T(E_T, j_1) > T_1(\text{min})$$

or

$$M_T(E_T, j_2) > T_2(\text{min})$$

$$T_1(\text{min}) = 20 + (M_{LQ} - 120) \text{ GeV}/c^2$$

$$T_2(\text{min}) = 20 + (M_{LQ} - 120)/2 \text{ GeV}/c^2$$



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Final Selection

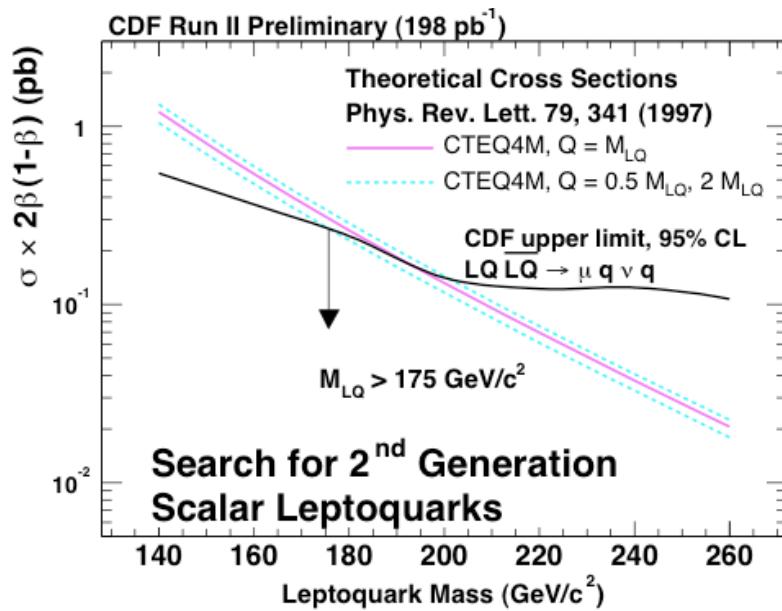
	140	160	180	200	220	240	260
W	0.92 ± 0.06	1.44 ± 0.10	1.44 ± 0.10	1.67 ± 0.11	1.65 ± 0.11	0.93 ± 0.06	0.44 ± 0.03
Top	1.69 ± 0.21	1.84 ± 0.23	1.35 ± 0.17	1.00 ± 0.39	0.80 ± 0.29	0.67 ± 0.08	0.52 ± 0.06
Z	0.18 ± 0.01	0.22 ± 0.02	0.19 ± 0.01	0.18 ± 0.01	0.14 ± 0.01	0.05 ± 0.00	0.04 ± 0.00
QCD	0.29 ± 0.29	0.29 ± 0.00					
Total	3.09 ± 0.57	3.74 ± 0.62	3.22 ± 0.56	3.08 ± 0.53	2.83 ± 0.51	1.94 ± 0.44	1.30 ± 0.39
Data	3	3	2	0	0	0	0

Luminosity 198pb^{-1}

Exclude at 95% CL
 $M_{LQ} < 175\text{ GeV}/c^2$



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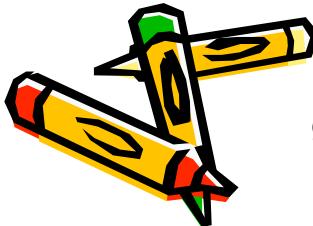
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Prospects for the future

2 fb^{-1}

Assuming the same acceptance as now

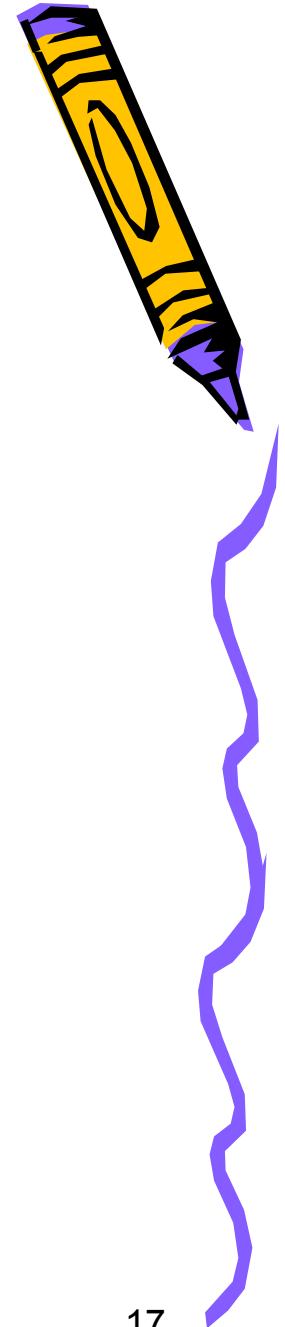
5 fb^{-1}



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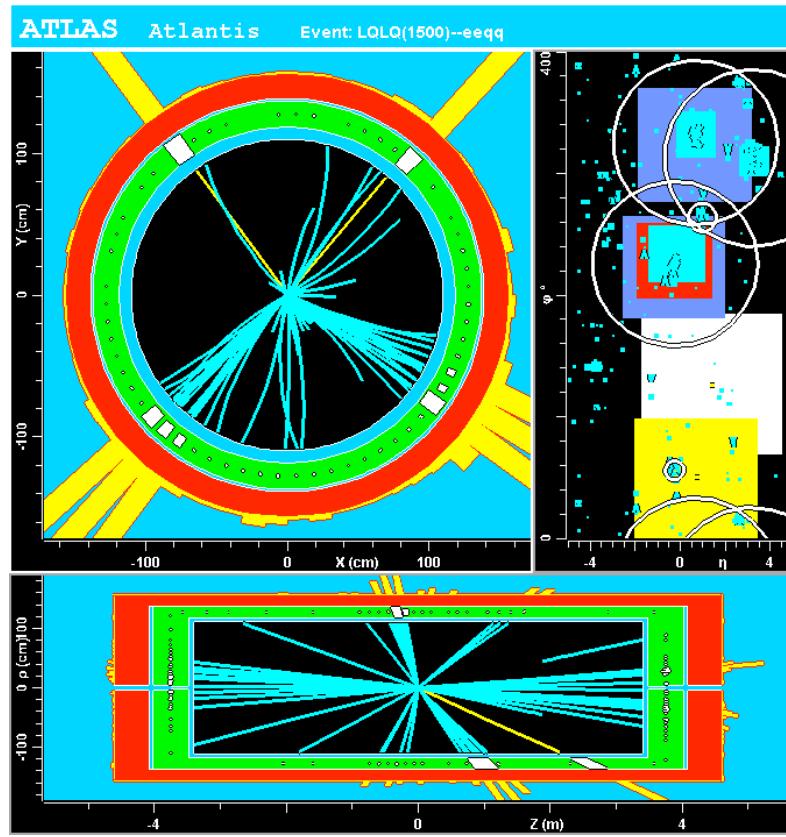


Leptoquarks in ATLAS

- Scalar leptoquarks production studied
- Pair production
 - $l\bar{l}jj$ channel
 - $l\Box jj$ channel
- Simulation tools:
 - PYTHIA
 - $qq \rightarrow LQ LQ$
 - $gg \rightarrow LQ LQ$
 - ATLAS fast simulation (ATHENA-ATLFAST)

LQ LQ $\rightarrow e^+e^-qq$
 $m_{LQ}=1500$ GeV
(schematic view)

V.A. Mitsou, I. Panagoulias, Th. Papadopolou,
Physics at LHC, Vienna 2004



2 leptons + 2 jets topology



Signal

$LQ \bar{LQ} \rightarrow l^+ q l^- \bar{q}$

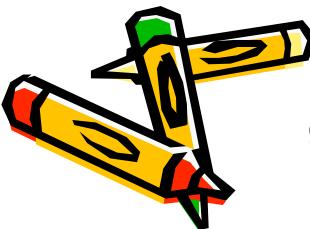
1st and 2nd generation LQs

M_{LQ} (TeV)	\Box (fb)	
	1 st gen.	2 nd gen.
1.0	5.0	4.8
1.2	1.3	1.3
1.3	0.71	0.68
1.5	0.22	0.21
1.7	0.074	0.070
2.0	0.015	0.014

Background

- QCD: huge, but eliminated after high- p_T isolated leptons and high- m_{lj} cuts are applied
- Drell-Yan: eliminated by high- m_{lj} cut

Process	$\Box \Box BR$ (pb)
Zjet ($l l jj$), $p_T > 20$ GeV	1 380
$t\bar{t}$ ($l l jj$)	11
ZZ ($l l jj$)	1.2
ZW ($l l jj$)	1.2
WW ($l l jj$)	3.3

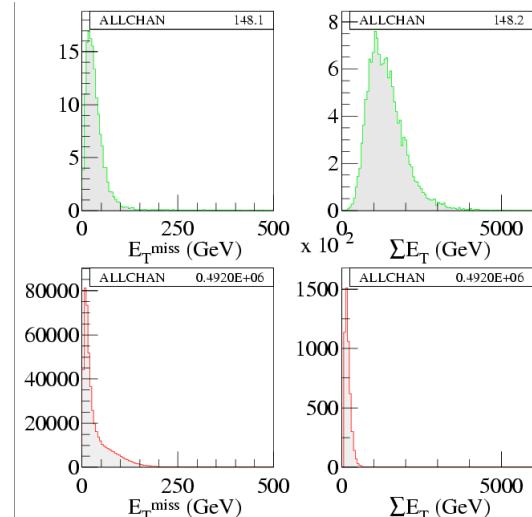
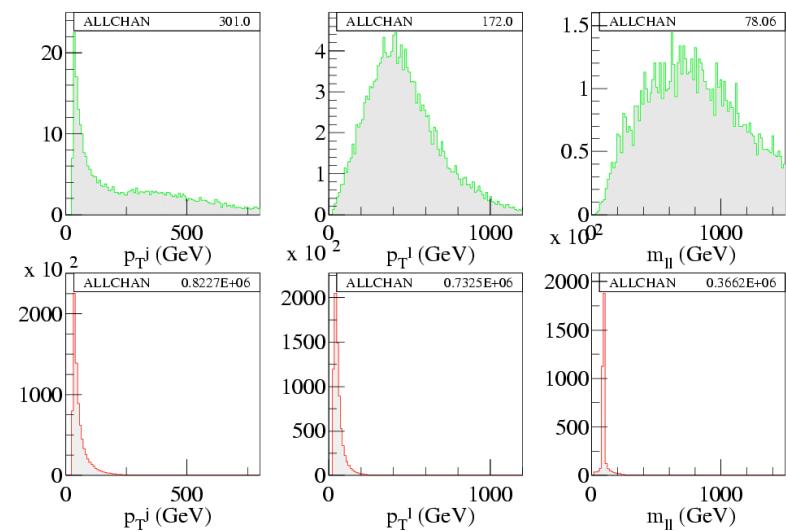


2 leptons & 2 jets topology

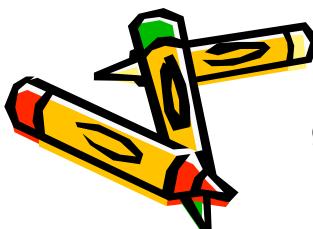
First level cuts:

At least **2 jets** with $p_T > 30 \text{ GeV}$ and $| \eta | < 5.0$

2 same-flavour, opposite-sign leptons with $p_T > 30 \text{ GeV}$ and $| \eta | < 2.5$



ΣE_T : sum of transverse energy in
the calorimeters



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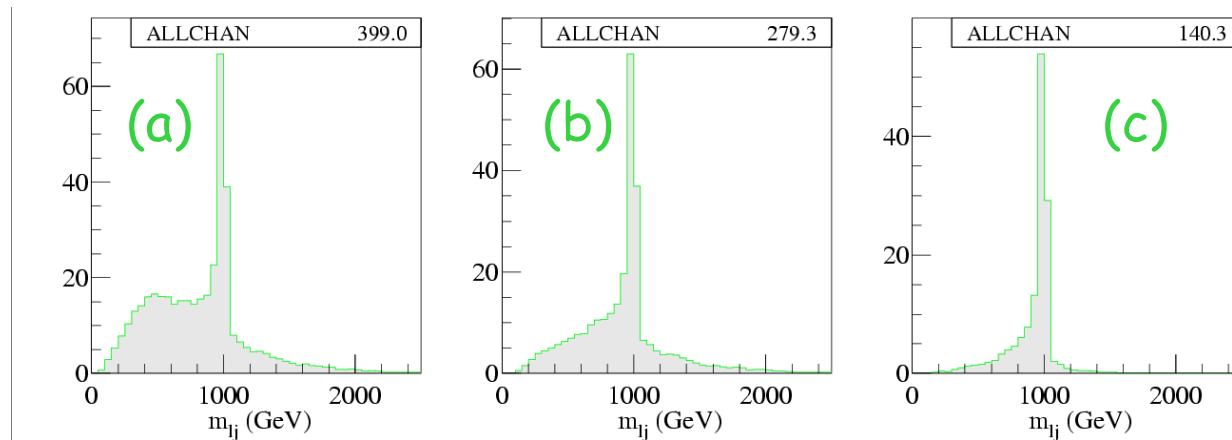
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$lljj$: m_{lljj} invariant mass

m_{lj} combination	$ m_{lj} - m_{LQ} < 100 \text{ GeV}$	
	# events	%
(a) all combinations	136/399	35%
(b) two leading jets	126/279	45%
(c) two leading jets; minimum- Δm_{lj} combination	98/140	70%

Provides
clearest
signal



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$m_{LQ}=1 \text{ TeV}$

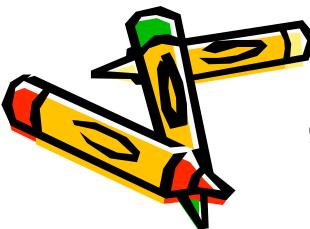
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$lljj$: selection cuts

- Similar cuts imposed for both eejj & $\mu\mu jj$ channels
- Cuts optimized to maximize significance for all leptoquark masses
 - at least 2 jets with $p_T > 70$ GeV and $| \eta | < 5.0$
 - 2 same-flavour, opposite- sign leptons with $p_T > 100$ GeV and $| \eta | < 2.5$
 - $M_{ll} > 180$ GeV (to remove Z events)
 - $E_T^{\text{miss}} < 70$ GeV (for tt background)
 - $\sum E_T > 570$ GeV
 - $E_T^{\text{miss}} / \sum E_T < 0.05$
 - mass window: $|m_{l_j} - m_{LQ}| < 100$ GeV
 - m_{LQ} reconstructed from two leading jets with minimum- Δm_{lj} combination

Preliminary



$lljj$: signal significance

- First generation leptoquarks
- Integrated luminosity ($L=30 \text{ fb}^{-1}$)

$M_{LQ} \text{ (TeV)}$	Signal	Background	S/\sqrt{B}
1.0	126	4.65	58
1.2	27.6	4.14	14
1.3	16.1	3.46	10.7
1.5	4.49	1.86	5.9

Preliminary

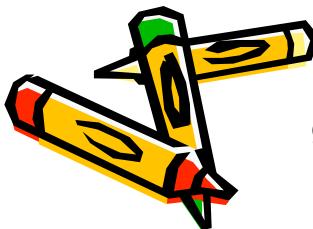
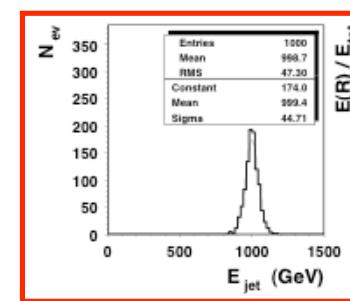
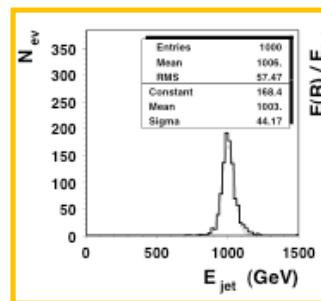
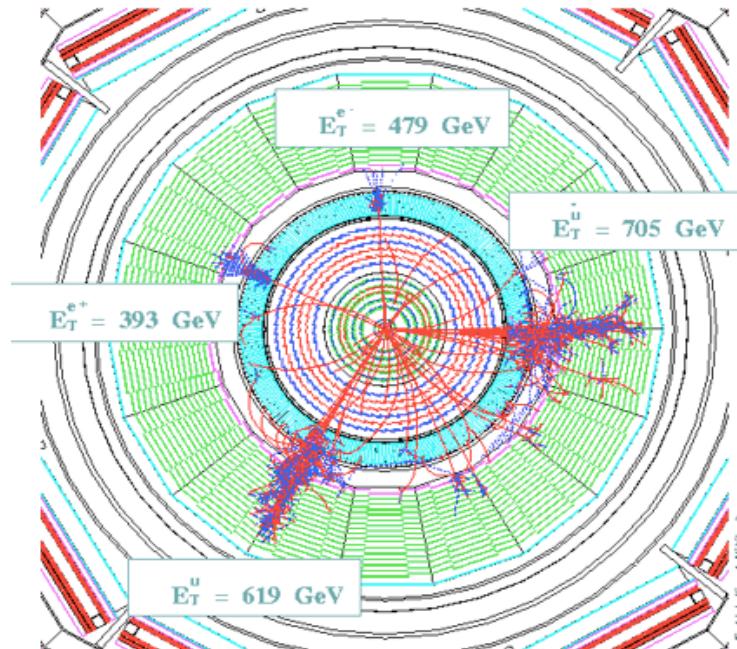
Signal can be clearly observed for $m_{LQ} = 1.3 \text{ TeV}$
Similar results obtained for $\square\square jj$ channel



LQ at CMS

- Scalar leptoquarks production studied
- Pair production
 - $l\bar{l}jj$ channel
 - $l\Box jj$ channel
- Simulation tools:
 - PYTHIA
 - $qq \rightarrow LQ LQ$
 - $gg \rightarrow LQ LQ$
 - CMSJET fast simulation (compared to CMSIM)

S. Abdullin, F. Charles
hep-ph/9905396

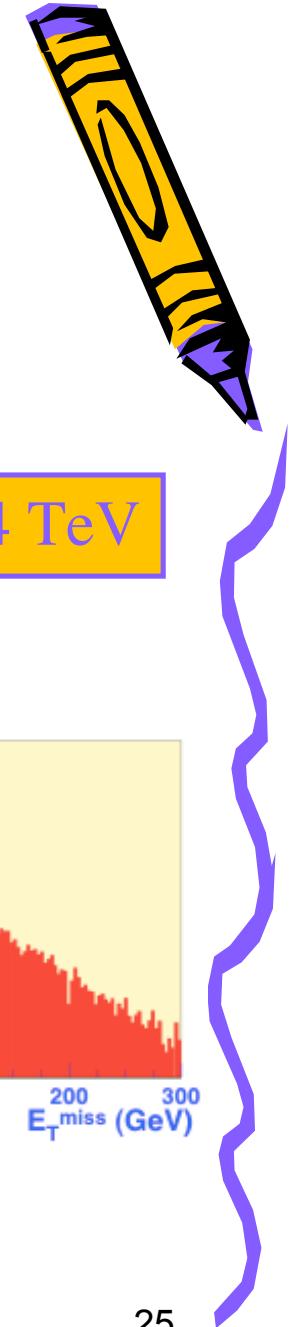


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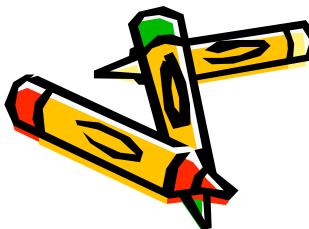
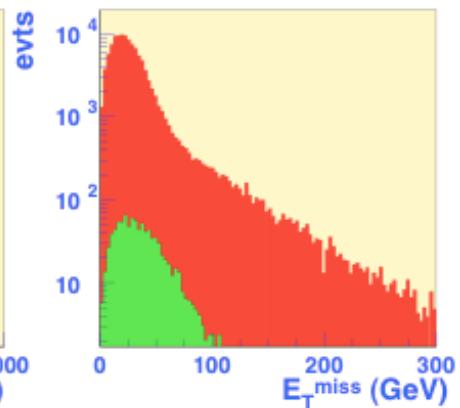
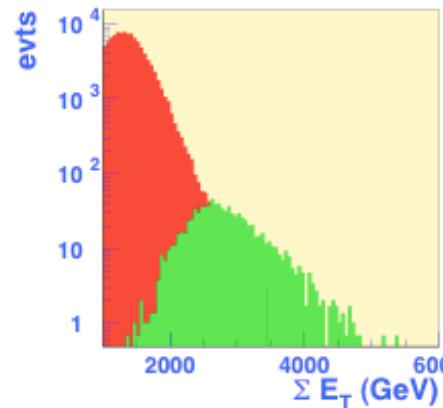
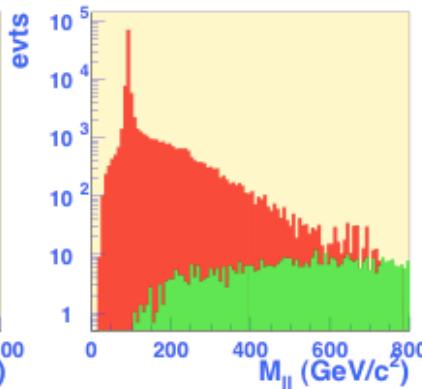
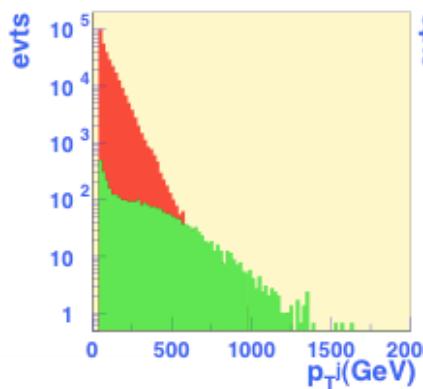
LQ at CMS



Selection cuts

- 2 isolated leptons (SF OS) with $p_T > 40$ GeV, $|\eta| < 2.4$; $m_{ll} > 150$ GeV
- At least 2 jets with $E_T > 60$ GeV , $|\eta| < 4.5$
- $E_T^{miss} < 185$ GeV, $\Sigma E_T > 1700$ GeV, $E_T^{miss}/\Sigma E_T < 0.04$
- $\Delta m_{lj} < 310$ GeV, the peak window $\Delta m = 210$ GeV

$m(\text{LQ}) = 1.4 \text{ TeV}$

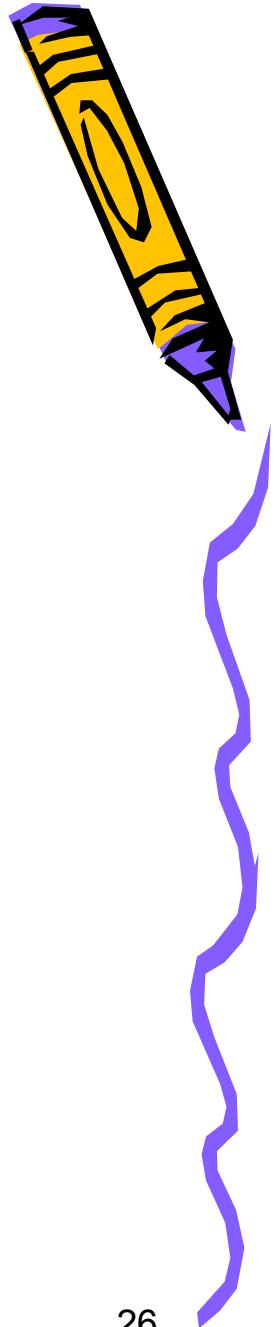


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LQ at CMS - sensitivity

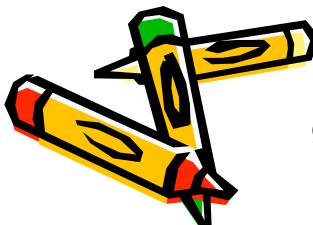


Accepted ij combinations and significance for $L = 100 \text{ fb}^{-1}$
eejj channel

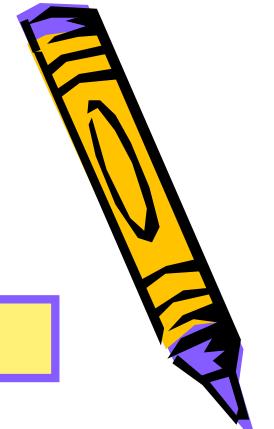


M_{LQ} (GeV)	900	1200	1400	1500
Signal	2584	174.4	49	24.6
Background	240	45.27	11.3	7.5
$\sigma = \frac{S}{\sqrt{S+B}}$	49	11.8	6.3	4.34
$\sigma = \frac{S}{\sqrt{B}}$	167	25.9	14.6	9.0

Expected 95% C.L. limit
 $m(LQ) < 1.47 \text{ TeV}$ for $\square = 1$
 $m(LQ) < 1.2 \text{ TeV}$ for $\square = 0.5$

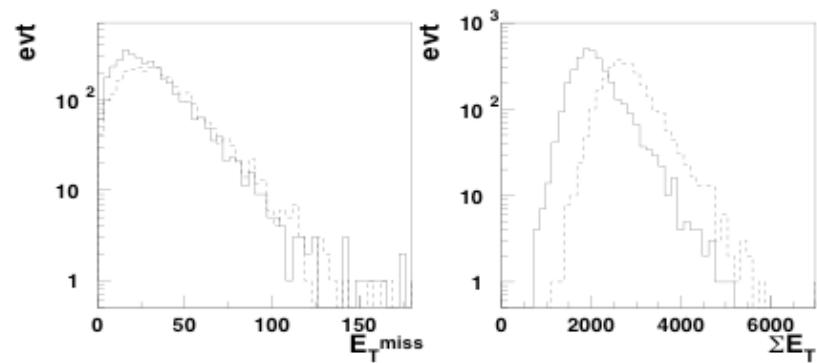


LQ at CMS - effects of pileup

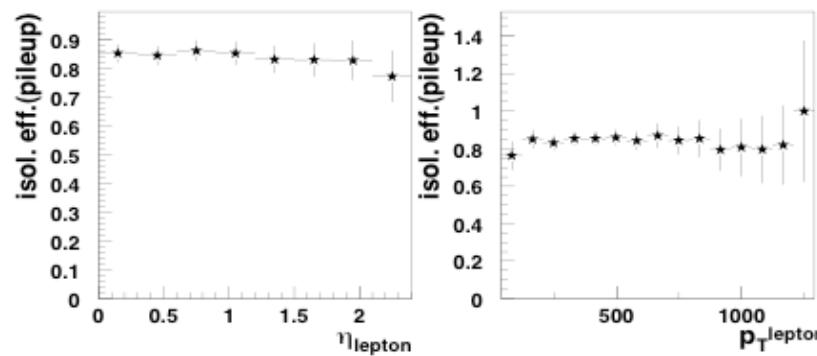


~25 interactions per bunch crossing at $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$

- E_T increase ~ 800 GeV;
- No considerable effect on MET
- Degradation of lepton isolation (both track-based and calo-based)



15% degradation
(p_T and □ dependence)



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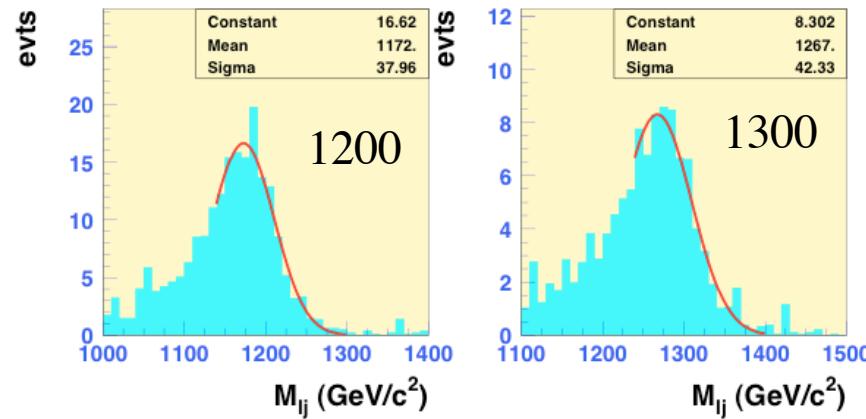
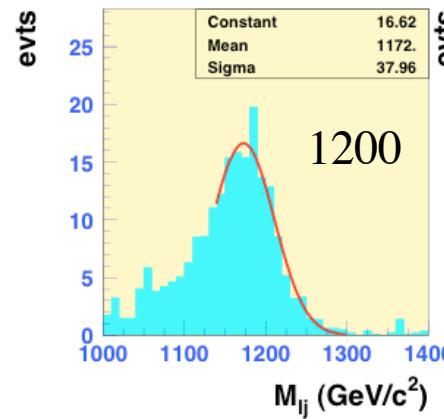
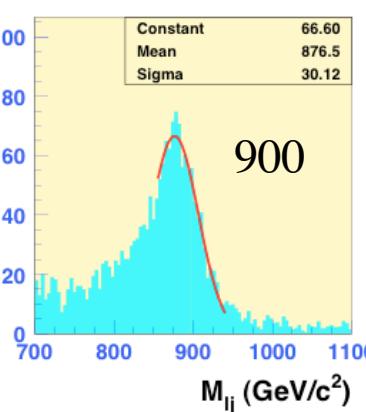
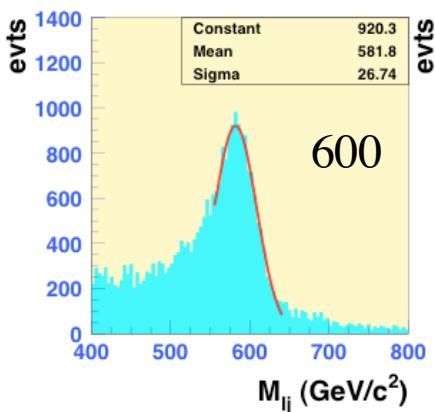
LQ at CMS - mass resolution

$$M_{LQ} = \sqrt{(\tilde{p}_l + \tilde{p}_{jet})^2} \simeq \sqrt{2E_l E_j (1 - \cos\theta)}$$

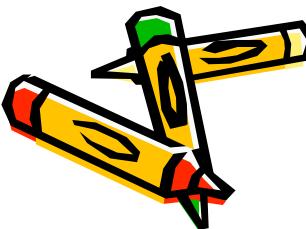
$$\frac{\sigma(M_{LQ})}{M_{LQ}} \simeq \frac{\sigma(E_j)}{2E_j}$$

due to the excellent lepton energy resolution in CMS

For high mass LQ and high energy jets the constant term dominates



$$\frac{\sigma(M_{LQ})}{M_{LQ}} \simeq \frac{6.5\%}{2} = 3.25\%.$$



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Conclusions

Searches for 1st and second generation LQ's are currently well established at the TeVatron;

Current limits are superseeding the existing ones from Run I
Choice of cuts very similar among the 2 experiments

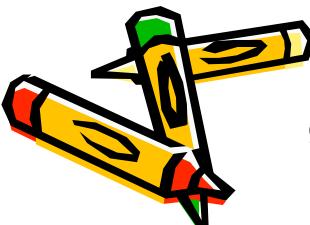
Final reach $\sim 300 \text{ GeV}/c^2$

Both ATLAS and CMS have carried on feasibility studies for searches for 1st and 2nd generation LQ

Cuts very similar to TeVatron

Issue of pile-up discussed in CMS

Final reach $\sim 1500 \text{ GeV}/c^2$



Thanks to the Organizers and Happy Landscaping !

